



# Multi-Scale Structural Mechanics and Prognosis

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*Integrity ★ Service ★ Excellence*

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# 2013 AFOSR SPRING REVIEW



NAME: David Stargel

## BRIEF DESCRIPTION OF PORTFOLIO:

**FLIGHT STRUCTURES:** Fundamental basic research into structural mechanics problems relevant to the US Air Force

**Structural mechanics** or **Mechanics of structures** is the computation of deformations, deflections, and internal forces or stresses (*stress equivalents*) within structures, either for design or for performance evaluation of existing structures\*

## LIST SUB-AREAS IN PORTFOLIO:

**Novel flight structures**  
**Multi-scale modeling and prognosis**  
**Structural dynamics**

## Focus w/in sub-areas

Computing  
Predicting  
Enabling

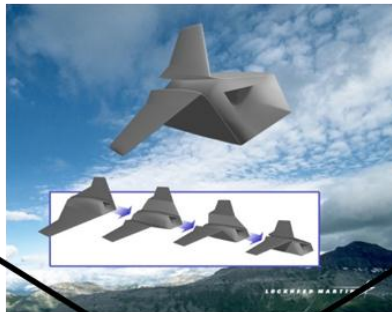
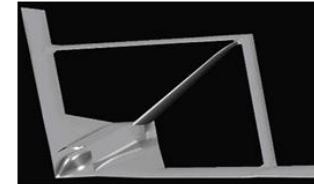
\* From Wikipedia



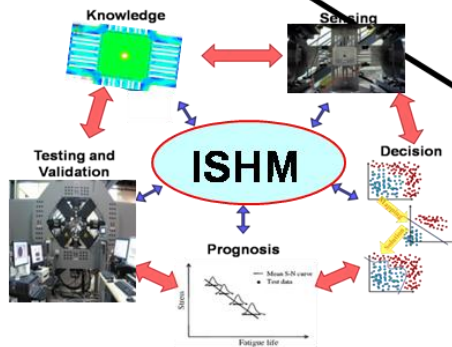
# Thrust Areas

## Novel Flight Structures

- Morphing Aircraft
- Flapping Wing Air Vehicles
- Non-traditional Structural Configurations

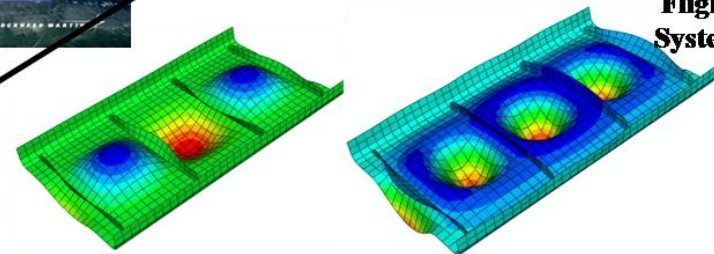


**Untested Flight System**



- Structural Health Monitoring
- Non-destructive Evaluation
- Prognostics
- Physics-based Modeling

## Multi-scale Modeling and Prognosis



- Thermo-acoustic Response
- Space Structures

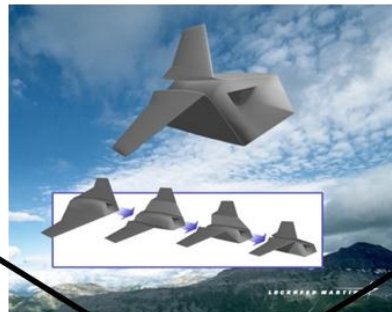
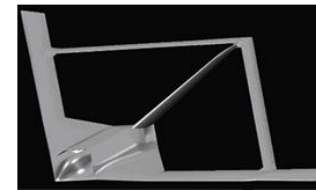
## Structural Dynamics



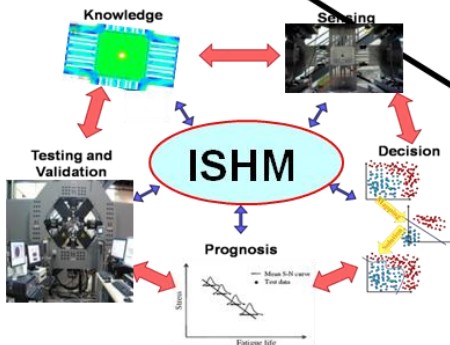
# Challenges

## Novel Flight Structures

- Multi-disciplinary Design Problems
- Non-traditional Structural Configurations
- Student Education

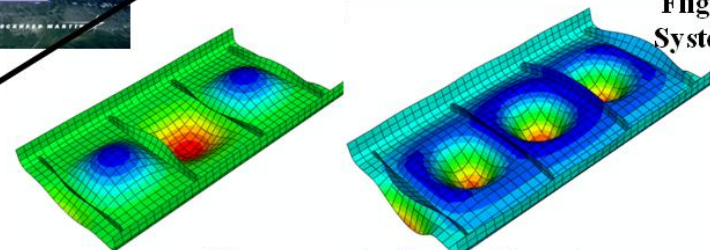


Untested  
Flight  
System



- Uncertainty/Variability
- Probability of Detection
- Verification & Validation
- Time & Length Scale Couplings

## Multi-scale Modeling and Prognosis



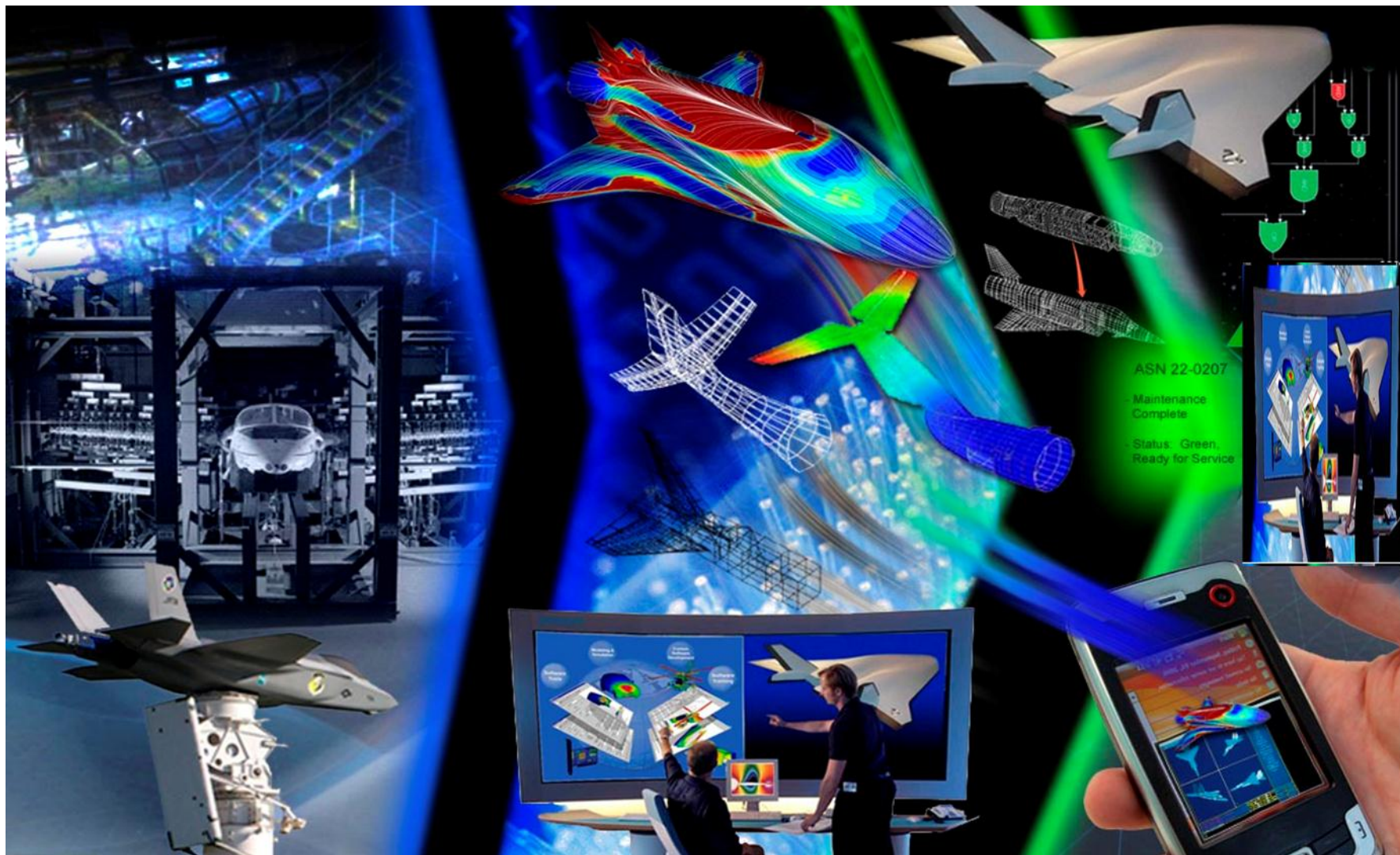
- Computation Cost
- Non-linear Interactions
- Testing Environments

## Structural Dynamics





# Structural Mechanics Vision of Future Weapon Systems



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# Exploratory & Anticipated Research



***"The first essential of the airpower necessary for our national security is preeminence in research..."***

**Gen. Henry "Hap" Arnold, 1944**



***"There was a view that we had advanced to a stage of aircraft design where we could design an airplane that would be near perfect the first time it flew. ... I think we've demonstrated in a compelling way that that's foolishness."***

**Gen. Norton Schwartz, USAF Chief of Staff From Defense News, 3/12/12**



**Seldom occurs as a result of addressing today's problems**



**New solutions to the direct projection of today's problems**





# Digital Twin Vision



## “Digital Twin”: Real-Time, High-Fidelity Operational Decisions for Individual Aircraft Enabled by Tail Number Health Awareness

- When physical aircraft is delivered, a **Digital Model** of the aircraft – specific to that tail number, including deviations from the nominal design – will be delivered as well.
- The **Digital Model** will be **flown virtually** through the same flight profiles as recorded for the actual aircraft by its **on-board SHM system**.
- The modeling results will be compared to sensor readings recorded by the SHM system at critical locations to **update / calibrate / validate** the model.
- As **unanticipated damage** is found, it will be added to the Digital Model so that the model continually reflects the **current state of the actual aircraft**.
- **Prognostics** for the airframe will be developed by “flying” the Digital Model through possible **future missions**.
- The Digital Model will be used to determine when & where structural damage is likely to occur, and when to perform maintenance.





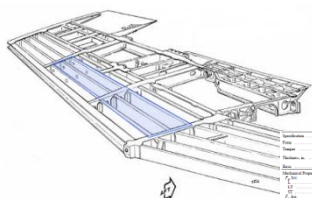
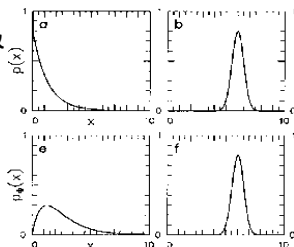


# Anticipated Digital Twin Research



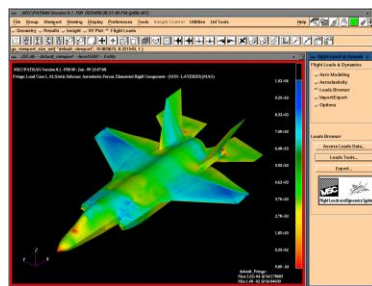
**Decision:  
Fly or Fix**

Applied Loads &  
Environments  
(Probabilistic)

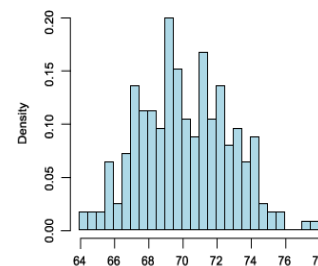


Geometry &  
Material Data  
(Probabilistic)

Element	Material	Property	Value
1	Aluminum	Young's Modulus	70.0 GPa
2	Aluminum	Poisson's Ratio	0.33
3	Aluminum	Density	2.70 g/cm³
4	Aluminum	Yield Strength	250.0 MPa
5	Aluminum	Tensile Strength	325.0 MPa
6	Aluminum	Elongation	12.0 %
7	Aluminum	Impact Strength	50.0 J/m²
8	Aluminum	Corrosion Resistance	Good
9	Aluminum	Thermal Expansion	23.0 µm/m°C
10	Aluminum	Thermal Conductivity	170.0 W/m°C



Physics-based Multi-  
scale, Multi-Discipline  
Models



Range of Structural  
Response & Reliability  
(Probabilistic)



# ***Quantification of Model Form Uncertainty in Physics-Based Simulations***



***Christopher Corey Fischer (WSU)  
MSTC-CCMS TAC Review  
14-15 November 2012***





# Uncertainty in ESAV Design



Representative ESAV N<sup>2</sup> Diagram

<b>Propulsion</b>	Flow behind inlet shocks	Flow-through panels' data	Temp., Press., Alt., M, Dimen.	Engine weight	Engine weight	Engine data in flight envelope	Thrust available for vectoring		Exhaust speed and temp.		Thrust, Altitude, Mach #, BPR, etc.
Cowl and Inlet	<b>Geometry</b>	Configuration, Mach #, Alt.	Cowl, Aft deck	Configuration	Tank and engine	Wing area	Control effector data	Configuration	Noise shielding factor	Configuration, Fuel volume	Configuration
		<b>Aerodynamics</b>	Skin temp., Loading	Aerodynamic Loading		Aero. data in flight envelope	Stability derivatives				
			<b>EEWS</b>	EEWS weight	Structural weight - EEWS						
				<b>Structures</b>	Structural weight - other					Structural failure	
					<b>Weights</b>	Aircraft weight in flight envel.	Inertial properties				Take-off gross weight
						<b>Mission Performance</b>				Fuel volume, Req. maneuvers	Feasibility
							<b>Stability and Control</b>			Added removed fuel volume	Feasibility
								<b>RADAR Cross Section</b>		RCS metric	
									<b>Noise</b>	Noise output	
										<b>Constraints</b>	Feasibility
Thrust, Altitude, Mach #, BPR, etc.	Configuration										<b>Optimization</b>



# Types of Uncertainty

Mathematical Model to Predict System Response

$$Y = g(X) + \epsilon$$

## Model Form Uncertainty

Present in having different models that represent the same system response, but not positive as to which one of these models is most accurate

- Adjustment Factor Approach
- Bayesian Model Averaging
- Probabilistic Adjustment Factors Approach

## Parametric Uncertainty

Inherent in input parameters within a model

- **Natural variability** in input parameters
- **Inconsistency** in manufacturing processes
- **Imprecise** statistical data

- Evidence Theory
- Probabilistic Analysis
- Sampling Approaches

## Predictive Uncertainty

Indicates variations in errors of a model's predictions

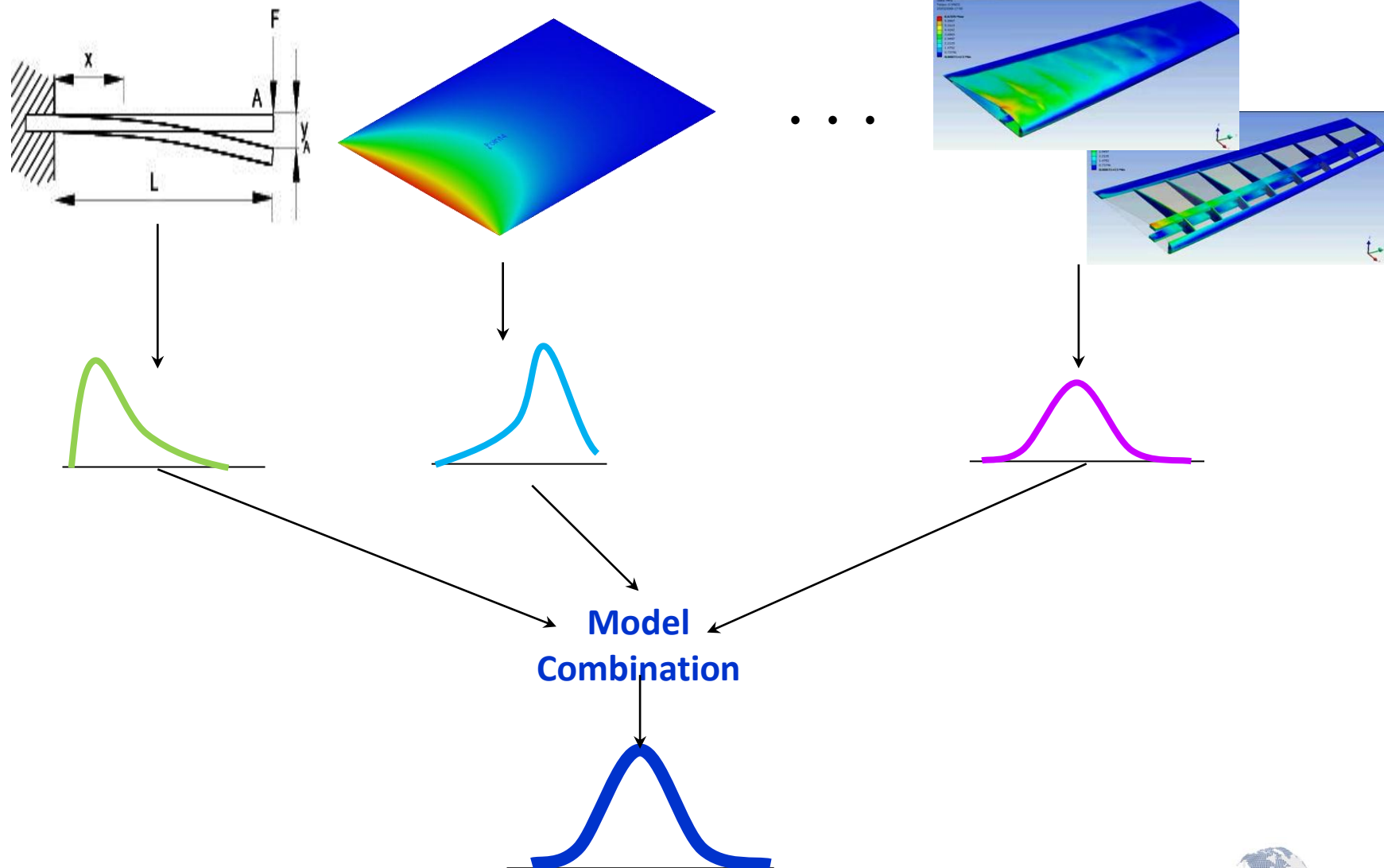
- **Differences** exist between observed experimental data and model predictions

- Bayesian Approach
- Regression Analysis





# Combination of Model-Form and Other Uncertainties





# Bayes' Theorem

- Bayes' theorem can be used to update prior model probability into posterior model probability given experimental data

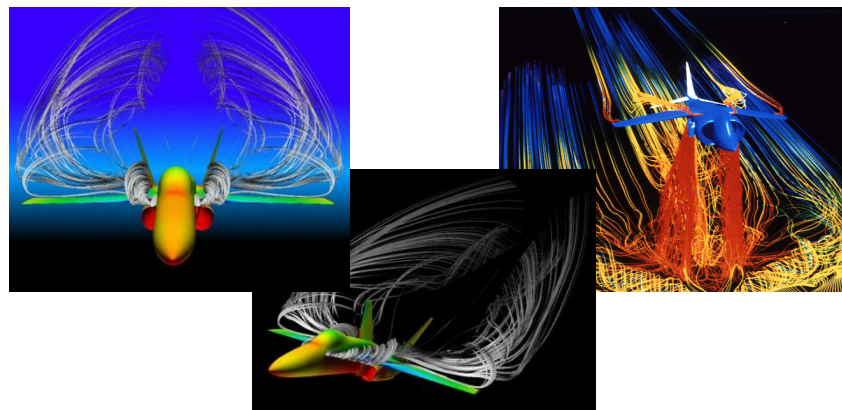
## Bayes' Theorem

$$P(M_j|D) = \frac{P(M_j)P(D|M_j)}{\sum_{i=1}^K P(M_i)P(D|M_i)}$$

## Model Likelihood

$$L(M_j|D) = P(D|M_j) = \left( \frac{1}{2\pi(\hat{\sigma})_{mle}^2} \right)^{N/2} e^{-N/2}$$

$$\text{where } (\hat{\sigma}_j)_{mle} = \sqrt{\frac{\sum_{i=1}^N \varepsilon_{j_i}^2}{N}}$$



Models 1 - K



Experimental Data





# Computational Prototype Design is part of ADT



10000s configurations

Conceptual Design Studies

Technology Suite

Prototype Representation  
10s configuration

## Dialable Fidelity

- Capture the phenomena driving the design
- Configuration & Flight Condition dependent
- Technology Suite Dependent

Prototype  
Experimental  
Validation

Prototype Analysis for Design

Prototype Design Space Exploration

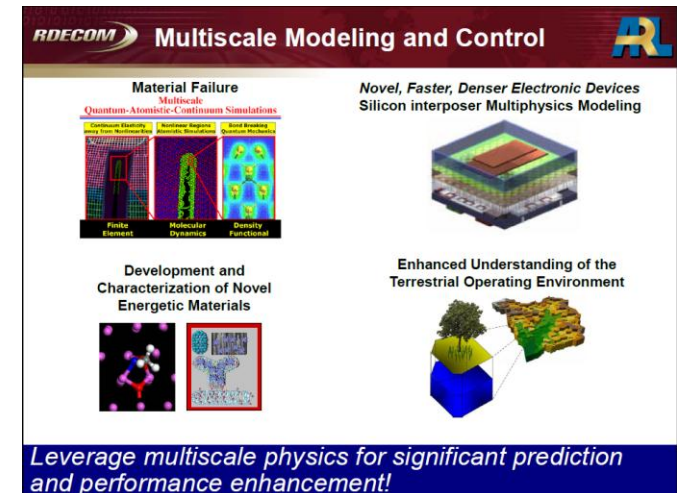
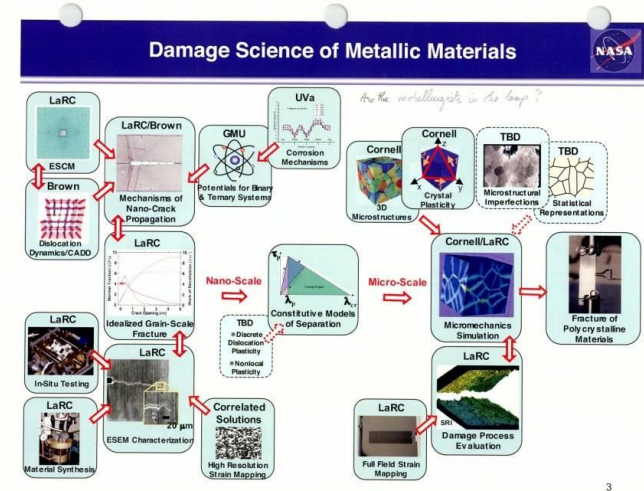
“Physics to Flight”



# Collaborations related to Digital Twin



- **NASA** - Ed Glaessgen/Steve Smith
- **ARO** - David Stepp
- **MURI on Uncertainty** – Fariba Fahroo
- **Mathematics for Multi-Scale Modeling** – Fariba Fahroo
- **Transformational Computing** – John Luginsland/Tatjana Curcic/Doug Smith
- **MURI on Hybrid Structures** – Joycelyn Harrison/Ali Sayir
- **AFRL/RX ICMSE** - Chuck Ward et al.
- **AFRL/RQ Airframe Digital Twin** – Eric Tuegel/Pam Kobryn
- **AFRL/RQ SSC** - Ravi Chona et al.
- **AFRL/RQ MSTC** – Ray Kolonay et al
- **ONR** - Bill Nickerson







# Enabling Methodologies



## Radical Change Applications

### Morphing



<http://www.flexsys.com/Projects/MACW/>

### Active Flow Control



<http://www.flexsys.com/>



### Air Force Actuation Needs:

- Large motions
- Radical shape change
- Distributed actuation
- Large force (level of aerodynamic loading)



### Active Membrane



### Deployment



# Photoresponsive Liquid Crystal Polymer Networks: Future Generation Adaptive Materials PI: Dr. Timothy White, AFRL/RX



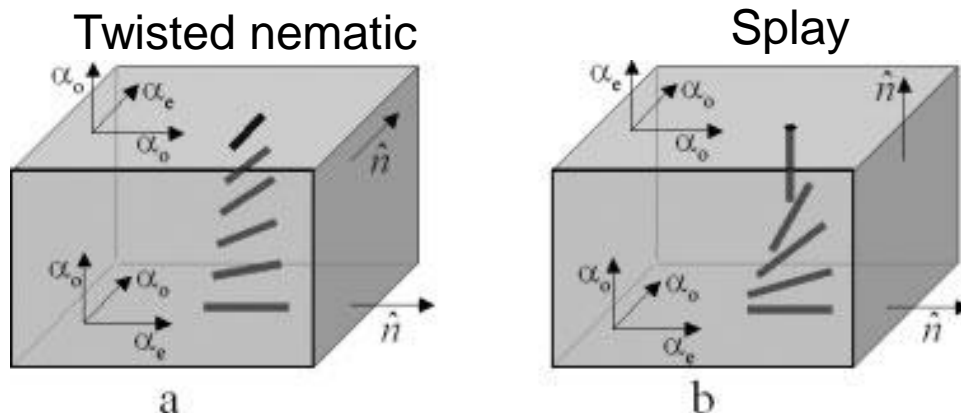
- Goal is to develop and characterize *wirelessly* triggered stimuli-responsive polymeric materials capable of *rapidly reversible* planar and flexural-torsional shape adaptations exhibiting both shape-restoring (muscle like) and shape-retaining (shape memory) behavior.
  - *Responsive liquid crystal polymer synthesis, development, and characterization for conventional, hierarchical (through thickness), and spatially ordered systems*
  - *Baseline polymer physics: correlated thermo-mechanical and photo-mechanical analysis*
  - *Development of spatially controlled adaptations*



# Liquid Crystal Polymer Networks (LCNs)



The orientation of the nematic director can be spatially varied through the thickness.

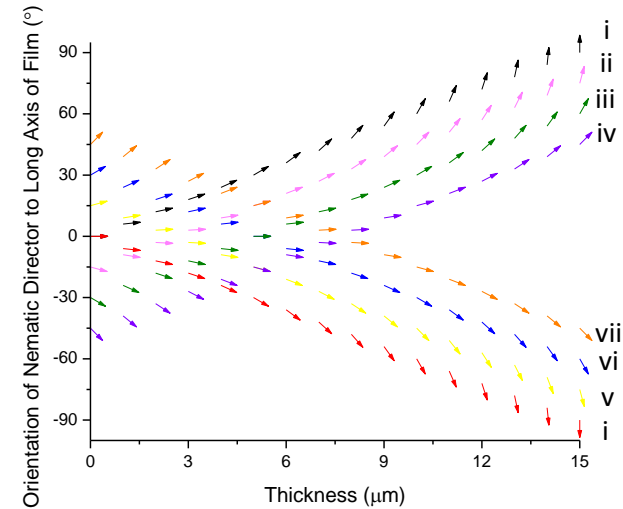
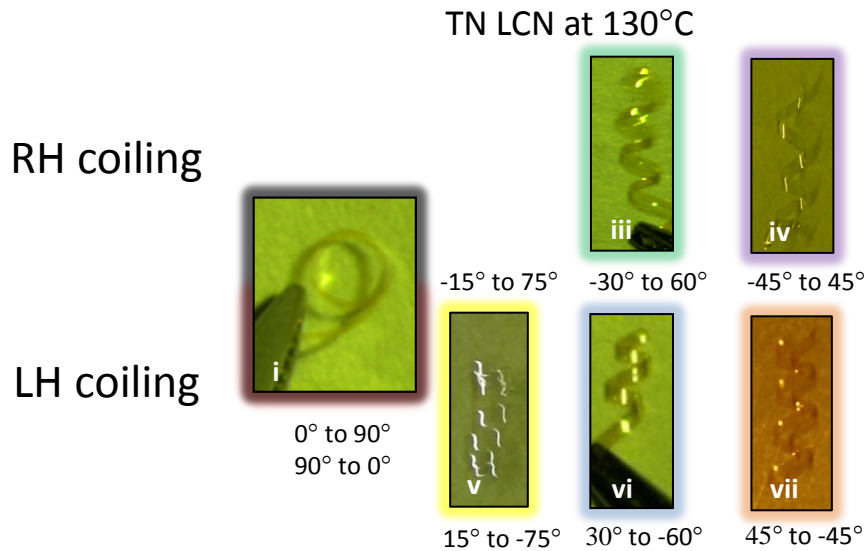


Broer et. al, Adv. Funct. Mater., 2005;  
Eur. Phys. J. E, 2007.

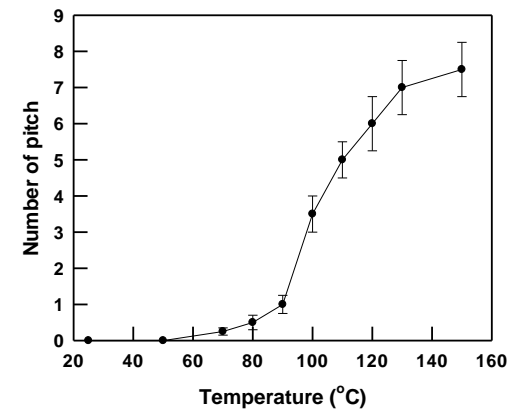
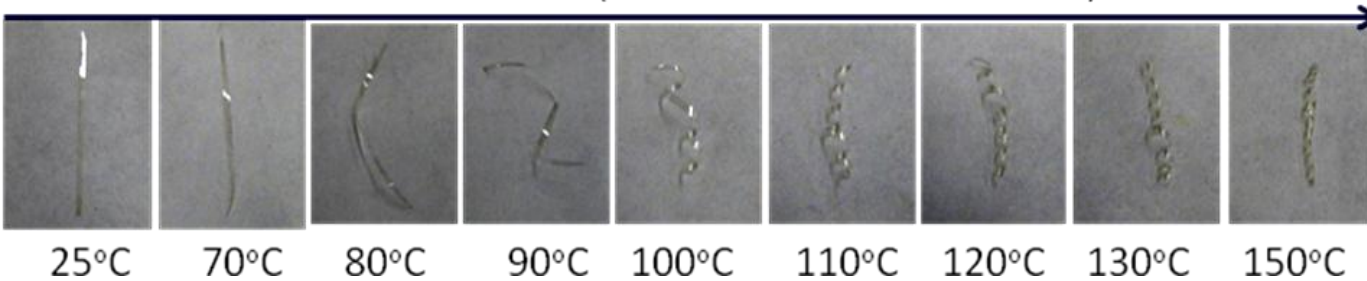
The resulting mechanical response is an interplay between the geometry of the film, the orientation of the liquid crystalline director (e.g. uniaxial, homeotropic, twisted, or splay) within the film, and the input stimulus (heat, light, electric field).



# Tuning the Shape – Varying Orientation and Temperature



Left handed (-30° molecular orientation)



Lee/White et. al, Adv. Mater., 2012

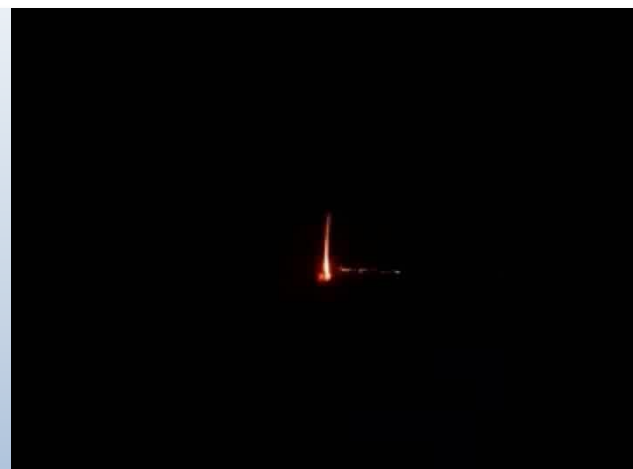
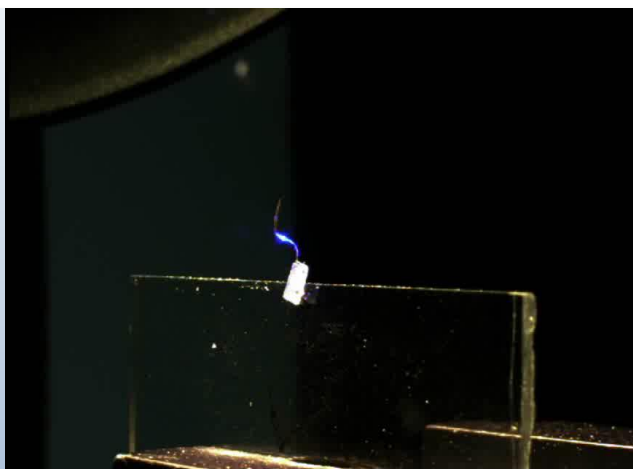
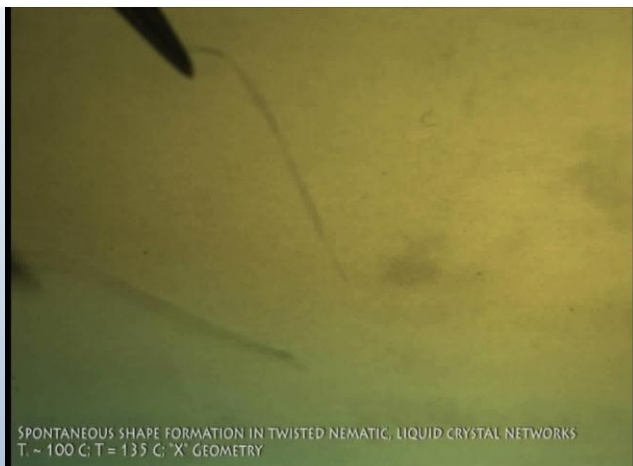
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# Populating material capability suite & exploiting design





# Multi-Scale Structural Mechanics Summary



- Three core thrusts along with the integrating vision of a Virtual Twin Concept
  - Spans Exploratory and Anticipated Research for:
    - Novel Flight Structures
    - Multi-scale Modeling and Prognosis
    - Structural Dynamics
- Program focuses on core concepts of structural mechanics
  - Computing
  - Predicting
  - Enabling
- Program is coordinated and actively collaborating with other government agencies and within AFOSR

